THE EFFECT OF CALCIUM SILICATE ON CATION EXCHANGE CAPACITY AND ON EXCHANGEABLE POTASSIUM, CALCIUM AND MAGNESIUM IN A FIELD TRIAL ON A HYDRIC DYSTRANDEPT

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INTRODUCTION

The soil from the Hamakua Experimental Farm, which is located on the humid Hamakua coast on the island of Hawaii, is derived from volcanic ash. Such soils derived from volcanic ash in the humid tropics are usually of agricultural importance.

The environmental conditions found on the Hamakua coast are favorable for the rapid alteration of the parent material. In this period of alteration, the ash soil loses most of its bases and will result in the accumulation of hydrated iron and aluminum oxides. As a result of this leaching of bases and the presence of iron and aluminum oxides, the soil tends to become acidic. This condition leads to changes in the availability of mineral nutrients and the soil also becomes generally unfit for good crop production.

Liming has long been the agricultural practice used in improving the pH in acid soils. Raising the pH of acid soils may increase the availability of several mineral nutrients and depress the solubility of elements which are toxic. Aside from raising the pH to a range better suited to crop nutrition, liming materials, such as $CaCO_3$ and $CaSiO_3$, also replenishes the calcium in calcium deficient soils.

The research reported here was designed to evaluate the effect of calcium silicate on: (a) soil pH and its relation to cation exchange capacity and (b) retention of exchangeable potassium, calcium, magnesium, and water-extractable silicon in the upper horizons of a Hydric Dystrandept profile.

REVIEW OF LITERATURE

I. Soil Acidity

Volcanic ash soils that have been exposed to intense weathering, lose most of their bases, while the hydrogen ion is accumulated in the presence of hydrous oxides of aluminum and iron. Following a stepwise hydrolysis, aluminum and iron compounds cause the release of H+ ions which then lower the soil pH. Hough, et al. (17) reported that the Hilo and Hamakua coastal soils suffered heavy losses of bases and silica while accumulating aluminum and iron within the profile.

Burgess (9) showed that the solubility of aluminum is related to pH, and he classified acidic soils of Hawaii in groups characterized by: (a) high acidity (pH 4.0-5.0) with active alumina of about 388 ppm and (b) low acidity (pH 5.0-5.8) with active alumina of about 36 ppm. Magistad (24) confirmed that the solubility of aluminum is related to pH. Paver and Marshall (32) stated that aluminum acts as an exchangeable base and may occupy a number of exchangeable sites in an acidic soil. This would lower the number of exchangeable sites available for basic cations and cause a subsequent decrease in base exchange capacity of the soil.

II. Soil pH and Cation Exchange Capacity

Due to the great reactivity of the amorphous fraction which possesses highly specific surface charges, soils originating from volcanic ash exhibit peculiar properties (23). Swindale (40) reported that it is unusual to find pH values below 5.0 in volcanic ash soils because of the high buffering capacity of allophane in the region of its

iso-electric point or the high buffering capacity of polymerized alumina gels. Birrell and Gradwell (7) reported that when the cation exchange capacity of allophanic soils was determined, variation in results were due to: (a) the concentration of the leaching solution, (b) the type of ions in the leaching solution, and (c) the volume of the washing alcohol.

Birrell (6) and Wada and Ataka (46) showed that CEC in allophane has values which are attributed to both permanent charges and pH-dependent charges. Hough, et al. (17) and Coleman, et al. (10) indicated that CEC in allophanic clays is caused by permanent charges which would arise from isomorphous substitution in the clay lattice. Contrary to permanent charge CEC, Hanna and Reed (15), Davis (11), Pratt and Hollowaychuk (34), and Pratt (33) illustrated the dependence of the cation exchange capacity on the pH of soils by using different methods of measurement. Schofield (85), showed that the negative charge on a subsoil was partially pH dependent.

Several investigators (16, 26, 27) showed that the CEC contributed by organic matter and clay varies at different soil pH values. Bartlett and McIntosh (3) and McLean, et al. (27) suggested that most of the increase in CEC resulting from liming was due to organic exchange sites previously inactivated by Al^{+++} ions. Greenland (14) proposed a mechanism by which organic materials could be bonded to clay particles when iron and aluminum hydroxides are polymerized at the clay surfaces. de Villiers and Jackson (12) also found an increase in CEC as a result of increased soil pH in moderately to highly weathered acid soils.

III. Liming Effects

In agricultural practices, application of liming materials has been the main method of raising soil pH. Voelcher (45) reported that liming with slag had a more lasting effect on soil reaction than quicklime. Application of calcium silicate has also been shown to have significant effects on crop yield (29, 37, 39). Increasing rates of calcium silicate also caused an increase in pH in some tropical soils (25, 29, 39).

A. Effect on cation exchange capacity

Onikura (31) and Tamimi, et al. (42) showed that cation exchange capacity increased with increasing rates of $CaSiO_3$ application. Onikura (31) concluded that the increase of cation exchange capacity in the surface soil was due mainly to the formation of stable amorphous aluminum silicate and not to the quantity or quality of the humus present. He also showed that the polymerization of silica increases the cation exchange capacity in an alkaline medium.

B. Effect on basic cations

With this increase in cation exchange capacity in the surface soils, it would be reasonable to expect greater retention of the cations. Ayres (1) demonstrated that potassium leached most slowly from limed latosols as compared to the unlimed latosols. Mahilum, et al. (25) showed an increase in retention of potassium, calcium and magnesium in a Hydro Humic Latosol profile with increasing rates of calcium silicate (slag). Seatz and Winters (36) also found that there was greater potassium retention when calcium rather than hydrogen was the

complementary ion. Syed-Fadzil (41) concluded that cation leaching decreased with increasing calcium silicate. It has been inferred that some exchange sites are specific adsorption sites for potassium (4, 8). Greater retention of potassium has also been found to be influenced by anion adsorption (2, 28). A thorough review of potassium and the factors that affect its movement in soils is given by Munson and Nelson (30).

MATERIALS AND METHODS

A. Soil Sampling Site and Soil Description

The sampling site for this experiment was the Hamakua Experimental Farm on the island of Hawaii, which is located at an elevation of 762 meters and has a mean annual rainfall of 230 centimeters. The mean annual maximum and minimum temperatures are 21.4 C and 14.0 C respectively. The soil is a silty clay loam which belongs to the Maile series, a Hydric Dystrandept developed from volcanic ash. The profile description of the Maile silty clay loam has been given by Uehara, et al. (43) (Table 3 in the Appendix).

Under virgin conditions, the Maile silty clay loam possesses the chemical analysis as described by Ikawa (19) (Table 4 in the Appendix). The X-ray diffraction patterns for the whole soil of the profile, illustrate an increase of amorphous material with increasing depth. The major crystalline peaks are quartz and magnetite (Fig. 6 in the Appendix).

B. Field Plots

The soil samples under investigation were collected from fertility plots that were established in 1967 for a 5 x 5 factorial on P X $CaSiO_3$ with three replications. Prior to the planting of corn, Zea mays L. (cultivar "Waimea Dent"), commercial calcium silicate was applied at rates of 0, 6.72, 13.44, 26.88 and 53.76 metric tons/hectare. This material has an analysis of 32.6% Ca, 22.2% Si, 0.041% K, and 0.022% P. The material was broadcast by hand on plots that measured 7.28 x 14.56 meters, and disc-plowed. Two weeks later, phosphorus was applied at the

rates of 0, 84, 168, 336, and 672 kilograms/hectare, as treble superphosphate, along with 84 kg N/ha, 336 kg K/ha, 134 kg Mg/ha and 45 Zn/ha. An additional 252 kg N/ha was applied during the growth of the plants. The second crop of corn (1968) received the same amount of N, P, and K along with 17 kg Cu/ha. A third crop of corn was planted during 1969, and received 364 kg N/ha, 336 kg K/ha and 134 kg Mg/ha.

Following a year of fallow (1970), a crop of Irish potatoes, Solanum tuberosum (var. 35-S), was planted in 1971 with the following nutrients applied: 336 kg N/ha, 336 kg K/ha, 22 kg B/ha and 11 kg Cu/ha.

C. Soil Sampling Procedure

A previous study on the same soil by Tamimi, et al. (42) showed no effect of phosphorus rates on soil cation exchange capacity. Subsequently samples were taken from plots that received a total of 672 kg P/ha at all rates of $CaSiO_3$ from all three replicates. Samples were obtained with a 10 cm diameter soil auger at 12 cm depth intervals, down to a depth of 91 cm. Extreme precautions were taken to avoid contamination by having the auger washed before sampling each layer. Soil samples from each layer were placed in double plastic bags and were taken to the laboratory where they were mixed thoroughly. A sub-sample was taken from each bag and was passed through a 20 mesh sieve.

D. Methods of Chemical Analyses

Chemical analyses were conducted to determine soil pH, CEC, exchangeable K, Ca, and Mg, extractable P and water extractable silicon.

Cation exchange capacity was determined by saturating the soil with N NH_4OAc adjusted to the pH of the soil as suggested by Tamimi, et al. (42).

1) Soil Moisture

Approximately 10 g of soil were placed in moisture cans, and soil moisture was determined by oven drying overnight at 105 C.

2) Soil pH

Approximately 15 g of soil were mixed with water in portion cups until a paste was formed. One hour was allowed for equilibration and the pH was determined using glass electrodes with a Beckman Expandomatic pH meter.

3) Cation Exchange Capacity

To 10 g (oven dry equivalent) of each soil sample, 200 ml of N NH_4OAc, adjusted to the pH of the soil were added and shaken in 500 ml Erlenmeyer flasks for 1 hour. Using vacuum suction, filtration was carried out with a Buchner funnel using Whatman No. 42 filter paper. The soil was washed with four 50 ml increments of N NH_4OAc, which had been adjusted to the pH of the soil, to completely saturate the soil cation exchange sites with ammonium ions. The filtrate and washings were saved for the determination of exchangeable cations. The soil retained on the filter paper was then washed with 200 ml of 95% ethyl alcohol in 50 ml aliquots. The washed soil and filter paper were then transferred to a 500 ml Erlenmeyer flask to which 200 ml of N KCl was added and shaken for one hour.

Using vacuum suction the soil was filtered and washed with another 200 ml KCl in 50 ml portions. The filtrate plus washings were transferred to 800 ml Kjeldahl flasks. A few drops of mineral oil, pieces of mossy zinc, glass beads and magnesium oxide were added. The NH_3 was distilled into 150 ml of saturated boric acid with several drops of mixed indicator (methylene blue and methyl red) until two-thirds of the extract was distilled. Standard sulfuric acid was used to titrate the distillate.

4) Exchangeable calcium, magnesium and potassium

Using the N NH_4OAc extract from the CEC determination, the cations were determined using the Perkin-Elmer model 209 atomic absorption spectrophotometer. To prevent interferences by other ions, the extract for each sample was diluted with 0.2% lanthanum oxide.

5) Water extractable silicon

Ten grams (oven dry equivalent) of soil were placed in 500 ml Erlenmeyer flasks and shaken for one hour with 200 ml of distilled water. After shaking, the solution was centrifuged at 1800 rpm for 15 minutes then filtered through a Whatman No. 42 filter paper.

Ammonium molybdate in sulfuric acid was added to an aliquot of the extract in 50 ml volumetric flasks to form a yellow silicomolybdate complex which was reduced to molybdenum blue (22). Color intensity was read on a Klett-Summerson

colorimeter with a 660 mμ filter.

E. Statistical Analysis

Analysis of variance was performed according to Snedecor (38) and significant differences between treatment means were determined using the Modified Duncan's (Bayesian) Least Significant Difference Test (13).

RESULTS

A. Effect of $CaSiO_3$ rates on soil pH and CEC in the soil profile

1) Soil pH

The various application rates of $CaSiO_3$ increased the pH of the soil. As the rates were increased from 0 to 53.76 metric tons of $CaSiO_3$ per hectare, the average pH within the soil profile increased significantly from 5.35 to 6.04 respectively ($P<.05$) (Table 5 in Appendix). The relatively small change in pH with this large amount of $CaSiO_3$ indicates that the soil is very highly buffered. These differences were significant over all rates except between 6.72 and 13.44 metric tons of $CaSiO_3$ per hectare treatments. The effect of $CaSiO_3$ throughout the profile is shown in summary in Fig. 1 and Table 5 in the Appendix. The pH is shown to increase significantly ($P<.05$) with increasing rates of $CaSiO_3$ down to 30 cm. Below this depth, only the 53.76 tons/ha $CaSiO_3$ treatment has pH values that are consistently higher than all of the other treatments.

At the 0 and 6.72 tons/ha $CaSiO_3$ treatments, the pH increased significantly with depth. The pH in the 13.44 and 26.88 tons/ha $CaSiO_3$ profile remained fairly constant but the 53.76 tons/ha $CaSiO_3$ shows some significant decreases of pH with depth. However, at lower depths of 61-91 cm, inherent properties of the soil probably come into the picture. With the 26.88 and 53.76 tons $CaSiO_3$ treatments, the pH was higher

at the surface than the underlying layers (Fig. 1).

2) Cation Exchange capacity of the soil

The cation exchange capacity of the soil increased significantly with applications of $CaSiO_3$ (Table 1). As the rate of application was increased from 0 to 53.76 tons $CaSiO_3$, the CEC increased from 48.63 to 63.65 me/100 g respectively, in the surface 15 cm. There was also a significant difference in CEC between the 6.72 and the 53.76 tons application rates down to 30 cm. Although there is a noticeable difference in CEC with the 53.76 tons treatment from all other treatments at the 0-30 cm depth, no statistically significant differences were found between all treatments below 30 cm. There was also a significant difference between the 53.76 tons $CaSiO_3$ and all other treatments in the average of the profile. The high CEC in the soil below 30 cm is probably caused by inherent properties of the soil, as shown by the X-ray diffraction (Fig. 6 in the Appendix) and also by the movement of basic cations down the profile.

B. Effect of $CaSiO_3$ on exchangeable cations in the profile

1) Retention of Potassium

A significant increase in exchangeable K near the surface was obtained as the $CaSiO_3$ rates were increased (Fig. 2). The exchangeable K increased from 91.7 ppm in the control to 276.7 ppm in the plots with 26.88 tons of $CaSiO_3$ applied. These

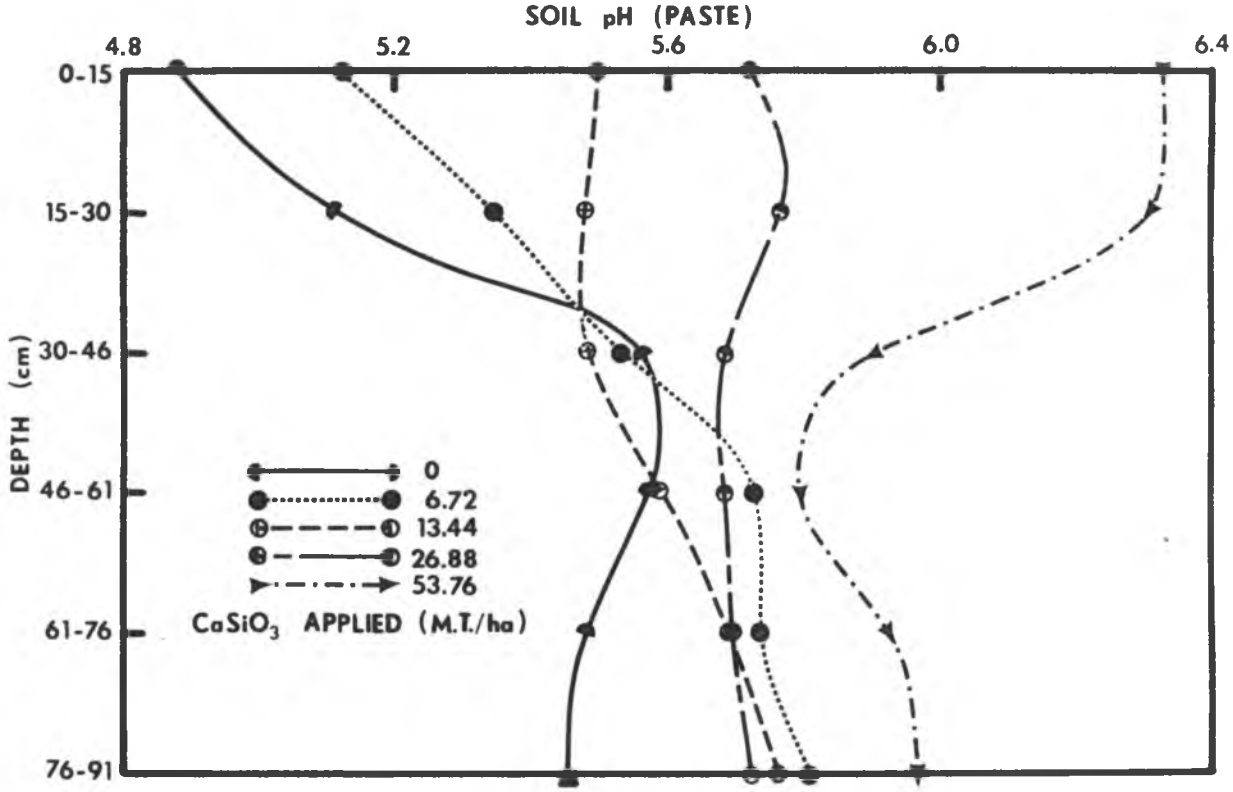

Fig. 1. Effect of $CaSiO_3$ on Soil pH at Different Soil Depths

Table 1. The effect of $CaSiO_3$ on CEC (me/100 g) with depth[1]

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)									
	0		6.72		13.44		26.88		53.76	
0-15	48.63	c	50.57	bc	53.68	bc	55.51	b	63.53	a
15-30	58.29	ab	52.35	b	58.49	ab	56.84	ab	75.94	a
30-46	62.09	a	56.64	a	57.78	a	66.11	a	80.15	a
46-61	64.28	a	74.83	a	60.72	a	65.32	a	71.91	a
61-76	76.25	a	87.53	a	68.45	a	68.96	a	86.74	a
76-91	84.91	a	73.22	a	77.78	a	89.88	a	86.89	a

[1]Averages of 3 replicates.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

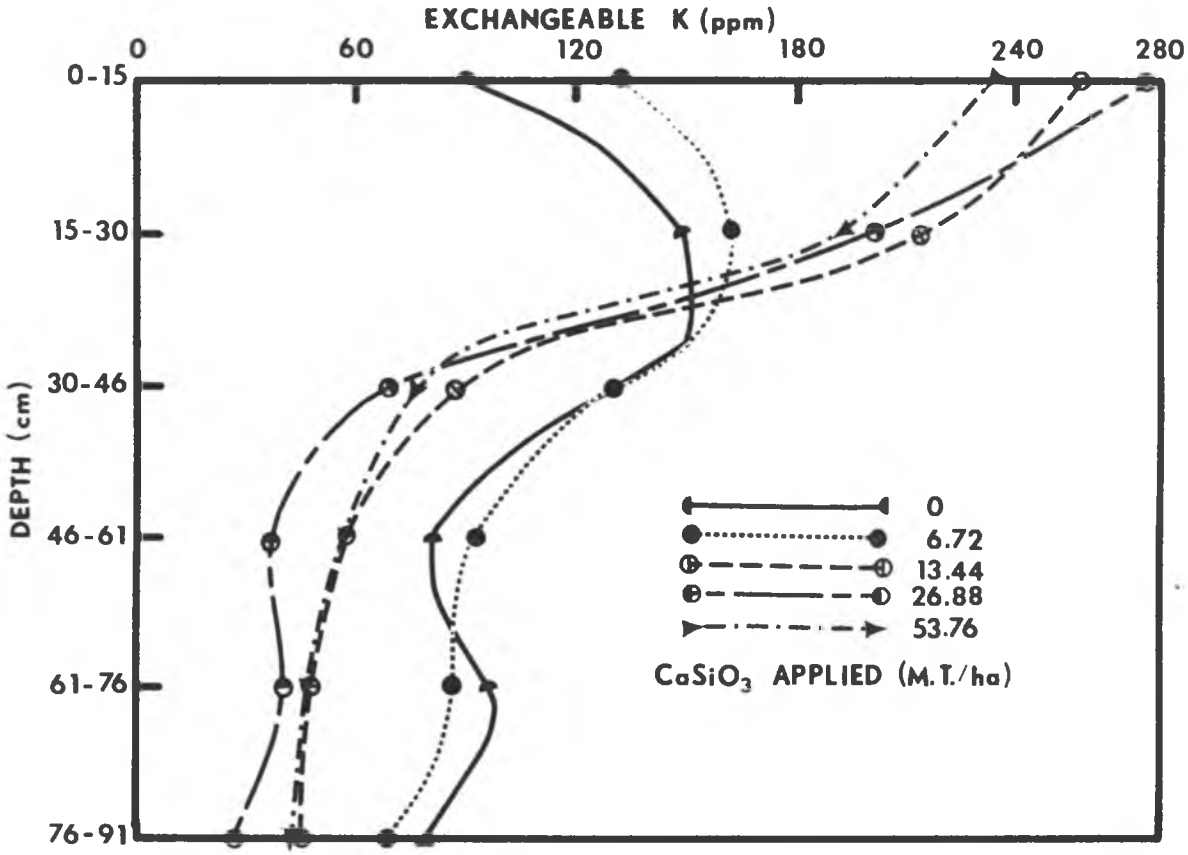

Fig. 2. Effect of $CaSiO_3$ on Exchangeable Potassium at Different Soil Depths

increases occurred in the 0-15 cm layer. At the 15-30 cm layer, there was a noticeably high retention of K at the higher rates of application (Fig. 2). However, these differences among all treatments were not found to be statistically significant. Below 30 cm, the rates of 0 and 6.72 had a considerably higher value for exchangeable K as compared to the rates of 13.44 tons $CaSiO_3$ and greater. This indicates that there was less leaching of K with increasing applications of $CaSiO_3$. Within each individual treatment, the lower application rates (0 to 6.72 tons) of $CaSiO_3$, exhibited no significant difference in K content throughout the profile (Table 6 in the Appendix). At application rates higher than 13.44 tons $CaSiO_3$, significant differences in K content appear to occur in layers above and below 30 cm. The leaching of K at the lower rates of $CaSiO_3$ reflects the effect of the significantly lower CEC on the surface layers in these treatments.

2) Retention of Calcium

There was a substantial increase of exchangeable Ca with depth with increasing $CaSiO_3$ rates. The increase at each depth was significant as far down as the 61-76 cm layer between the 0 and 53.76 tons of $CaSiO_3$ applications (Fig. 3 and Table 8 in the Appendix). The average exchangeable calcium in all depths of the profile show a significant increase from 263 ppm to 2337 ppm between the 0 and 53.76 tons $CaSiO_3$ respectively (Table 14 in the Appendix). On the surface 30 cm the exchangeable Ca increased with increasing rates of $CaSiO_3$ from an average of

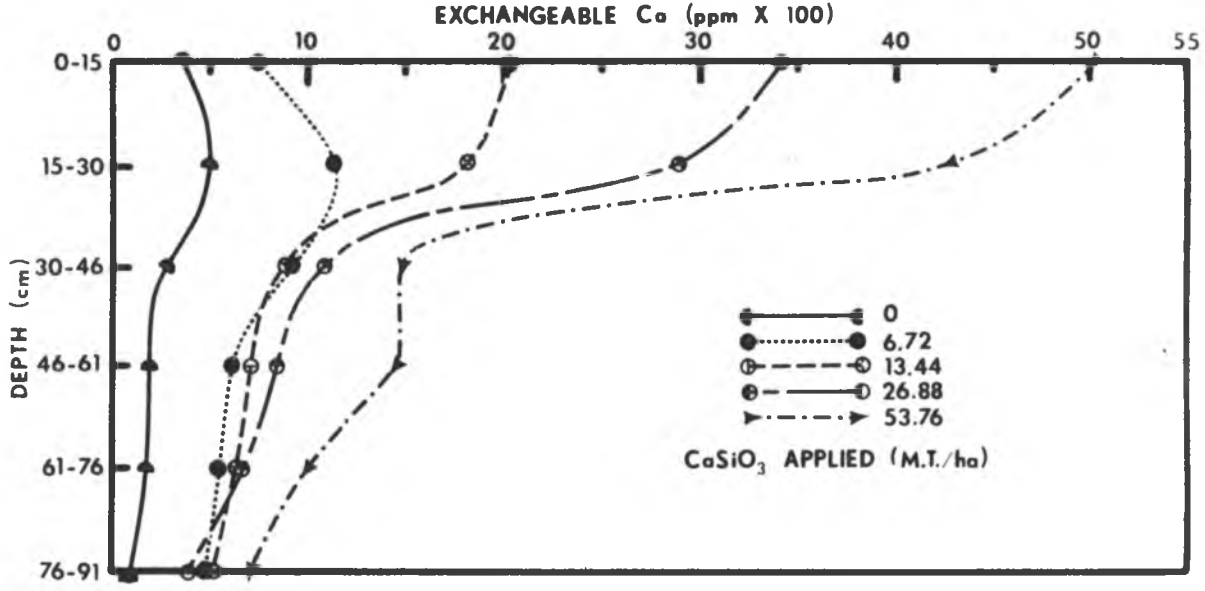

Fig. 3. Effect of $CaSiO_3$ on Exchangeable Calcium at Different Soil Depths

434 to 4691 ppm with the 0 to 53.76 tons $CaSiO_3$ applied respectively. On a percent basis, higher percentages of exchangeable Ca in a profile was found at the surface of plots with higher rates of $CaSiO_3$ applied (Table 9 in the Appendix). This shows that with the increased rates of $CaSiO_3$, greater retention of Ca occurs. The increase in exchangeable Ca within a profile resulted from the increased quantity of Ca applied with increasing rates of $CaSiO_3$.

3) Retention of Magnesium

With increasing rates of $CaSiO_3$, exchangeable Mg in the surface 15 cm increased significantly from 14.5 ppm to 148.7 ppm with the 0 and 53.76 tons of applied $CaSiO_3$, respectively (Fig. 4). This significant difference among rates is visible down to a depth of 61 cm. At the rate of 6.72 tons $CaSiO_3$, a significant increase of Mg occurred with depth but at the rates of 13.44 tons $CaSiO_3$ and higher, the results are reversed, that is, greater amounts of exchangeable Mg was found in the surface 30 cm than at the lower depth. This indicated that at the higher rates of $CaSiO_3$ greater retention of exchangeable Mg occurred at the surface. The low amount of exchangeable Mg at all depths investigated in the control plots may be due to mineral fixation or leaching of Mg beyond the 91 cm depth (Fig. 4 and Table 10 in the Appendix).

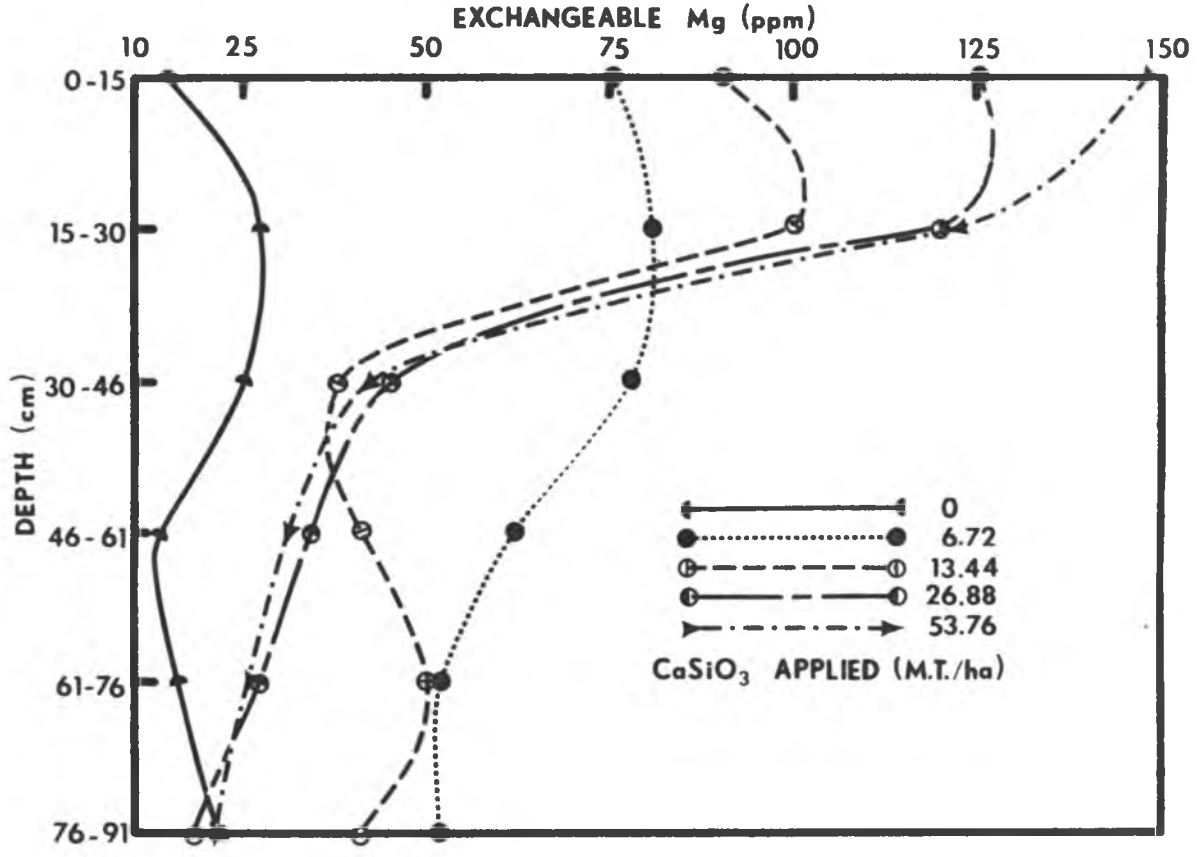

Fig. 4. Effect of $CaSiO_3$ on Exchangeable Magnesium at Different Soil Depths

C. Water-extractable Silicon

Water-extractable silicon increased significantly with increasing rates of $CaSiO_3$ as far down as the 46 cm depth (Fig. 5 and Table 12 in the Appendix). Beyond this depth, no difference occurred with treatment. This may indicate that significant leaching of Si occurred only to a depth of 46 cm. It also appears that water-extractable Si in the soil constitutes a very small portion of the total silicon applied.

D. Effect of pH of $\underline{N}$ NH_4OAc Extracting Solution on Cation Exchange Capacity and Extractable Cations and Silicon

CEC, exchangeable calcium, magnesium and potassium from selected samples were extracted by two methods: (a) using $\underline{N}$ NH_4OAc adjusted to pH 7.0 and (b) $\underline{N}$ NH_4OAc adjusted to the pH of the soil. Results obtained from the test comparing the two methods indicate that there is no significant difference between the two methods in the determination of calcium, magnesium and potassium (Table 2). However, at rates below 26.88 tons/ha of $CaSiO_3$, a significant difference between the two methods were observed in CEC. Most of the CEC values determined at the pH of the soil were lower than those determined at pH 7.0. The amount of silicon extracted was significantly higher using $\underline{N}$ NH_4OAc adjusted to the pH of the soil.

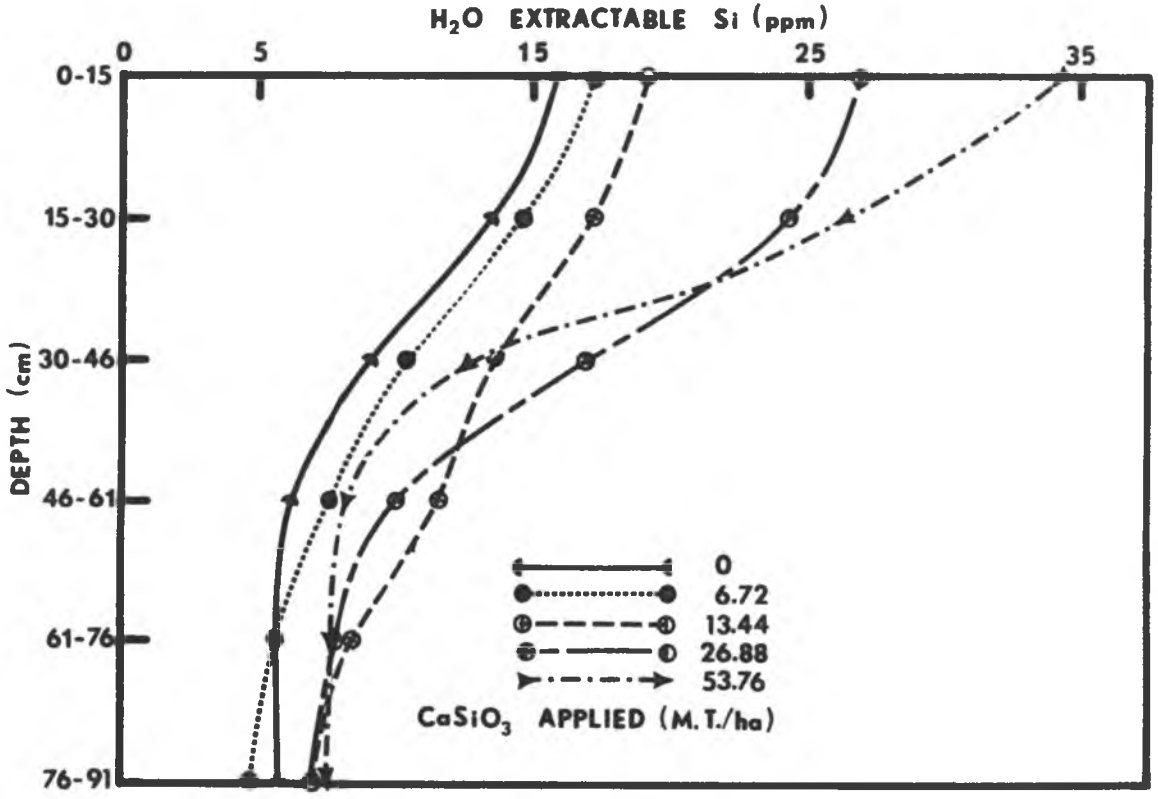

Fig. 5. Effect of $CaSiO_3$ on Water Extractable Silicon at Different Soil Depths

Table 2. The effect of pH of N NH_4OAc on CEC, Extraction of Cations, and Silicon

Treatment $CaSiO_3$ (M.T./ha)	(kg/ha)	Depth (cm)	pH	CEC (me/100 g) pH-7.0	CEC (me/100 g) pH-Soil	K (ppm) pH-7.0	K (ppm) pH-Soil	Ca (ppm) pH-7.0	Ca (ppm) pH-Soil
0	672	0-15	5.01	65.1	48.7	27.0	27.0	23	24
0	672	15-30	5.21	82.0	53.2	22.2	22.2	18	17
0	672	30-46	5.56	109.4	91.3	35.4	46.8	18	12
0	672	46-61	5.49	139.9	116.8	42.6	52.2	13	12
6.72	672	0-15	5.35	125.8	49.8	78.0	79.8	416	528
6.72	672	15-30	5.44	113.2	51.9	96.0	98.0	432	600
6.72	672	30-46	5.56	125.9	55.2	124.0	123.0	416	472
6.72	672	61-76	5.78	159.3	108.9	105.0	104.0	384	400
13.44	672	0-15	5.35	76.7	54.6	242.0	250.0	1424	1664
13.44	672	15-30	5.49	81.7	64.8	253.0	253.0	2016	2144
13.44	672	30-46	5.10	57.7	67.8	120.0	126.0	1080	1320
13.44	672	76-91	5.64	58.8	107.8	64.8	69.0	784	832
26.88	672	0-15	5.72	61.4	60.6	316.0	328.0	2960	3280
26.88	672	15-30	5.85	63.2	64.7	284.0	268.0	3440	3400
26.88	672	46-61	5.55	76.3	75.2	46.2	51.0	776	872
26.88	672	61-76	5.52	72.2	77.2	57.6	70.8	600	648
53.76	672	0-15	6.31	67.7	67.8	166.0	176.0	5280	5440
53.76	672	15-30	6.00	65.0	69.9	194.0	200.0	4640	4720
53.76	672	46-61	5.59	60.2	58.3	38.4	47.4	2304	2304
53.76	672	76-91	6.24	125.7	62.9	26.4	27.6	672	704
				r = .320		r = .998**		r = .998**	

Table 2. (Continued) The effect of pH of N NH_4OAc on CEC, Extraction of Cations, and Silicon

Treatment $CaSiO_3$ (M.T./ha)	(kg/ha)	Depth (cm)	pH	Mg (ppm) pH-7.0	Mg (ppm) pH-Soil	Si (ppm) pH-7.0	Si (ppm) pH-Soil
0	672	0-15	5.01	5.8	4.8	10.4	43.8
0	672	15-30	5.21	2.9	3.1	9.0	34.0
0	672	30-46	5.56	4.4	5.3	4.8	19.1
0	672	46-61	5.49	4.8	4.6	6.4	27.1
6.72	672	0-15	5.35	12.0	14.0	11.4	27.6
6.72	672	15-30	5.44	35.0	39.0	8.8	21.2
6.72	672	30-46	5.56	57.0	56.0	7.4	25.0
6.72	672	61-76	5.78	54.0	55.0	6.4	23.4
13.44	672	0-15	5.35	62.0	68.0	18.3	33.5
13.44	672	15-30	5.49	122.5	123.0	13.3	32.9
13.44	672	30-46	5.10	46.5	51.5	9.8	.39.8
13.44	672	76-91	5.64	64.0	65.0	6.4	18.1
26.88	672	0-15	5.72	102.5	107.5	32.9	43.8
26.88	672	15-30	5.85	124.0	116.0	41.2	51.0
26.88	672	30-46	5.55	37.5	38.0	20.2	38.8
26.88	672	76-91	5.52	31.6	32.0	5.8	24.2
53.76	672	0-15	6.31	155.0	150.0	56.0	55.2
53.76	672	15-30	6.00	125.0	123.0	48.6	62.7
53.76	672	46-61	5.59	28.0	25.0	5.8	16.7
53.76	672	76-91	6.24	21.6	21.0	5.5	15.4
				r = .998**		r = .875**	

DISCUSSION

The study of the retention of soil exchangeable cations is of great importance in agriculture, since the mobility of exchangeable bases determines to a great extent the availability of nutrients to plants. The results presented in the earlier section show the effect of $CaSiO_3$ on soil pH, on CEC and on the retention of basic cations.

Increasing the rates of $CaSiO_3$ significantly increased both the soil pH and exchangeable calcium in the profile. The control plots exhibited an increase in soil pH with depth. The acidic condition at the surface may be the result of the hydrolysis of aluminum or the presence of organic acids. Contrarily, the higher pH at the lower depths may be due to both the inherent properties of the soil or by the movement of the basic cations down the profile. At the higher rates of $CaSiO_3$ application, 26.88 and 53.76 tons/ha, the pH is higher at the surface than in the subsoil because of the greater retention of the basic exchangeable cations. This increase of pH in the surface soil with increasing rates of $CaSiO_3$ is in agreement with works by Bartlett and McIntosh (3) and Mahilum, et al. (25).

Bhumbla and McLean (5) indicated that exchange sites were released when Al ions were converted to $Al(OH)_3$ in limed soils. Mahilum, et al. (25) also found a decrease in exchangeable Al with increasing pH in volcanic ash soils. If this is the condition that prevails in this soil, then these exchange sites could be filled with the Ca^{+2} ions. On the hydrolysis of $CaSiO_3$ the following reaction may occur: $CaSiO_3 + 2H_2O \rightleftarrows Ca(OH)_2 + H_2SiO_3$. The concentration of OH^- ions associated with

the calcium may cause an increase in soil pH. The increase of exchangeable Ca with increasing $CaSiO_3$ rates correlates with the increasing pH of the corresponding treatment. Organic matter within the soil behaves as a weak acid with weakly ionized H^+ ions (35), which means that the H^+ ions can be easily dissociated, replaced with Ca^{+2} ions and reflect a rise in pH with an increase in CEC.

Schofield (35) stated that CEC can be attributed to two types of charges on clays: (a) permanent charge, in which the magnitude and strength of charge remains unchanged with pH changes and (b) pH dependent charges, which is weakly acidic in character. In the latter case, with increased pH the H^+ ions can be easily dissociated and could possibly cause the increase in CEC. According to Loganathan (23), soils of the Maile series show a decrease in negative charges with decreasing pH. Accordingly, an increase in negative charges due to the increase in soil pH, may result in an increase in CEC. The higher CEC values with depth may be caused by the greater surface area at lower depths of the profile where the soil contains amorphous constituents which exhibits irreversible dehydrating material. This is demonstrated by the increasing soil water content with depth (Table 16 in the Appendix). The surface soil may be lower in CEC owing partly to the susceptibility of being dehydrated into irreversible material, which has a smaller surface area and charge (21).

The increase of CEC with increasing rates of $CaSiO_3$ in the surface soil is caused by the increase of pH. This is in agreement with Bhumbla and McLean (5) and de Villiers and Jackson (12) who found increasing CEC of acid weathered soils or clays with increasing pH. de Villiers and

Jackson (12) further explained that the increased CEC with increased pH resulted from the release of initially blocked isomorphous substitutional negative charges in clay as a deprotonation of the hydroxy alumina present.

Tamimi, et al. (42) showed that the determination of CEC with N NH_4OAc at pH 7.0 did not correlate with the soil pH. However, when determined with N NH_4OAc adjusted to the pH of the soil, the results were highly correlated with the soil pH. This shows that the CEC in this soil is pH dependent. At the rates of 26.88 tons $CaSiO_3$ and higher, the difference in CEC between the two methods become negligible. This could be caused by the neutralization of negative charges by specifically adsorbed calcium as described by Syed-Fadzil (41). The extraction of exchangeable Ca, Mg, and K had no significant differences when extracted by the two methods. This indicates that the proper CEC of the soil should be determined at the pH of the soil. By using this method, a more exact base saturation can be determined. Van Raij and Peech (44) had recently suggested that methods should be modified in determining CEC in some soils as opposed to the use of standard procedures.

High rates of $CaSiO_3$ enhanced the retention of exchangeable K within the surface soil. This is in agreement with results reported by Mahilum, et al. (25). At lower rates of $CaSiO_3$, however, the K content was found to be higher in the subsoil as compared to the higher $CaSiO_3$ treatments. This indicates that greater leaching of exchangeable K occurred at the lower rates of $CaSiO_3$ which may be due to the lower CEC at the surface. Tamimi, et al. (42) found that maximum retention of exchangeable K in the surface 15 cm occurred at 53.76 tons $CaSiO_3$. The

probable explanation for the maximum exchangeable K occurring at the 26.88 tons $CaSiO_3$ in this investigation may be due to experimental error or the limited area of the soil sampled for this investigation.

Exchangeable Ca was found to have substantially increased throughout the profile as the rates of $CaSiO_3$ were increased. This, however, does not necessarily indicate that Ca is readily leached but possibly caused by the large quantity of Ca applied to the plow layer at the high rates of $CaSiO_3$. Although leaching took place, a greater percentage of exchangeable Ca was retained in the surface as the rates of $CaSiO_3$ were increased. This retention was possibly the result of increasing CEC with increasing soil pH. Jarusov (20) concluded that the mobility of exchangeable cations depends on the degree of saturation of the adsorbents with the cation. The increase in pH and CEC with the 53.76 tons $CaSiO_3$ treatment can be correlated with the increase in exchangeable Ca down to the 46 cm depth.

All of the plots received a blanket application of 403 kg Mg/ha over the period of the experiment. The application of $CaSiO_3$, which has 0.48% Mg also contributed 4.8 kg Mg/ha which would mean an additional 258 kg Mg/ha at the 53.76 ton $CaSiO_3$ level. This accounts for the significant increase of the average exchangeable Mg of the overall profile with increasing rates of $CaSiO_3$. However, the data reveal that as the rates of $CaSiO_3$ increased, the proportion of the surface retained Mg to the total amount of applied Mg increases. This indicates that there is increasing retention of exchangeable Mg in the surface which is again probably caused by the increased CEC with the increasing soil pH.

The increase in water-extractable silicon showed no relation to the increase in pH or CEC when the percent in each layer was taken. The

content of silicon seems to be controlled mainly by the amount that is applied.

SUMMARY AND CONCLUSION

The effect of $CaSiO_3$ applied to a Hydric Dystrandept on soil pH, CEC, exchangeable K, Ca, and Mg, and water-extractable silicon was investigated. Rates of $CaSiO_3$ applications were 0, 6.72, 13.44, 26.88, and 53.76 metric tons/hectare. Soil samples were taken at 15 cm increments to a depth of 91 cm.

With the increasing rates of $CaSiO_3$, there was an increase in soil pH to a depth of 30 cm. The more pronounced increases were at the rates of 26.88 and 53.76 ton/ha of $CaSiO_3$. As the soil pH increased, an increase in soil CEC was also observed with increasing rates of $CaSiO_3$.

The increase of CEC in the 0-15 cm depth was from 48.63 me/100 g in the control to 63.53 me/100 g in the soil treated with 53.76 ton/ha $CaSiO_3$ rates respectively. Increasing the CEC of the soils resulted in a greater retention of K, Ca, and Mg against leaching in the surface 0-30 cm. Six years after the application of $CaSiO_3$, silicon had been leached only to a depth of 46 cm.

Twenty samples were used to compare two methods of extraction: (a) $\underline{N}$ NH_4OAc adjusted to the soil pH and (b) $\underline{N}$ NH_4OAc adjusted to pH 7.0. No significant differences were found between the two methods in the extraction of K, Ca and Mg. At the lower rates of $CaSiO_3$, CEC determined at pH 7.0 was higher than those determined at the soil pH. However, at 26.88 ton/ha $CaSiO_3$ and higher, differences in CEC between the two methods become negligible. This indicates that CEC determined at pH 7.0 in low pH soils with pH-dependent charges, may be invalid. Since soil CEC increases by increasing the pH of acidic soils, extraction of

exchangeable cations from these soils with NH_4OAc at pH 7 would result in erroneous values for both CEC and percent base saturation.

Results from this study show that liming materials can be used as a tool in field management for nutrient availability and that the pH of the extracting solution for CEC and exchangeable cations, presents new parameters for soil classification. If it is desirable to increase the content of exchangeable K, Ca, Mg or any other cation in the subsoil, low levels of $CaSiO_3$, or any liming material should be used. Also, depending on the buffering capacity of the soil, higher rates of lime could be applied to prevent the leaching of these exchangeable cations.

APPENDIX

Table 3. Profile description of the maile silty clay loam (43)

Horizon: A11(RSL No. 6590)

Description: 0 to 5 cm (0-2 inches), dark reddish brown (5YR 2/2) silt loam, black (2.5YR 2/1) dry; moderate fine subangular blocky structure; hard, friable, slightly plastic; many roots; many fine pores; medium acid (pH 6.0): abrupt smooth boundary.

Horizon: A12(RSL No. 6591)

Description: 5 to 10 cm (2-4 inches), dark reddish brown (5YR 2/2) cindery sandy loam, dark brown (10YR 3/3) dry; moderate fine subangular blocky structure; hard, friable; many roots; common fine black cinders and charcoal; medium acid (pH 6.0); abrupt smooth boundary.

Horizon: A13(RSL No. 6592)

Description: 10 to 35 cm (4-14 inches), very dark brown (10YR 2/2) silty clay loam, dark brown (10YR 3/3) dry; strong fine subangular blocky structure; extremely hard, friable, slightly sticky, plastic, smeary; many roots; many fine pores; slightly acid (pH 6.1); clear wavy boundary.

Horizon: B21(RSL No. 6592)

Description: 35 to 43 cm (14-17 inches), dark yellowish brown (10YR 3/4) silty clay loam dark brown (7.5YR 3/3) dry; weak coarse prismatic structure breaking to moderate fine subangular blocky structure; very hard, friable, slightly sticky, plastic, weakly smeary; many roots; many fine pores; slightly acid (pH 6.2); clear smooth boundary.

Table 3. (Continued) Profile description of the maile silty clay loam (43)

Horizon: B22(RSL No. 6594)

Description: 43 to 50 cm (17-20 inches), dark brown (10YR 3/3) silty clay loam, very dark brown (10YR 2/2) dry; weak coarse prismatic structure breaking to moderate fine subangular blocky structure; very hard, friable, sticky, plastic, weakly smeary; common roots; many fine pores; slightly acid (pH 6.2); clear smooth boundary.

Horizon: B23(RSL No. 6595)

Description: 50 to 60 cm (20-24 inches), dark yellowish brown (10YR 3/4) silty clay loam very dark brown (10YR 2/2) dry; weak coarse prismatic structure breaking to moderate fine subangular blocky structure; very hard, friable, sticky, plastic, weakly smeary; few roots; slightly acid (pH 6.5); clear smooth boundary.

Horizon: 11C(RSL No. 6596)

Description: 60 to 73 cm (24-29 inches), dark brown (10YR 3/3) silty clay loam, very dark brown (10YR 2/2) dry; structureless, massive; hard, firm, slightly sticky, slightly plastic, weakly smeary; tuff band; few roots; many fine pores; slightly acid (pH 6.5); abrupt smooth boundary.

Horizon: 111B24b(RSL No. 6597)

Description: 73 to 90 cm (29-36 inches), dark brown (7.5YR 3/4) silty clay loam, very dark brown (10YR 2/2) dry; weak medium and fine subangular blocky structure; very hard, friable, sticky, plastic, moderately smeary;

Table 3. (Continued) Profile description of the maile silty clay loam (43)

few roots; many fine pores; common patchy glaze; neutral (pH 6.6); abrupt smooth boundary.

Horizon: 111B25b(RSL No. 6598)

Description: 90 to 120 cm (36-48 inches), very dark brown (10YR 2/2) silty clay loam, (10YR 2/2) dry; weak coarse and medium prismatic structure breaking to moderate medium and fine subangular blocky structure; very hard, friable, sticky, plastic, moderately smeary; few roots; many fine pores; common patchy gelatinlike coatings on peds; tuff band about 5 cm (2 inches) thick; neutral (pH 6.6); abrupt smooth boundary.

Horizon: 111B26b(RSL No. 6599)

Description: 120 to 150 cm (48-60 inches), very dark brown (10YR 2/2) silty clay loam, very dark grayish brown (10YR 3/2) dry; weak medium subangular blocky structure; friable, sticky, plastic, moderately smeary; few roots; many fine pores; neutral (pH 6.6).

Table 4. Chemical analyses of Maile silty clay loam (19)

Depth (in.)	Horizon	pH(H_2O)	Organic Carbon	Organic Matter	Extrac. Fe %	Extractable Bases (me/100 g) Ca	Mg	Na	K	CEC me/100 g
0-4	A1	4.54	13.97	24.1	14.13	1.83	0.47	0.15	0.18	68.04
4-13	A21	5.00	11.99	20.7	11.67	0.58	0.15	0.15	0.07	72.25
13-19	A23	5.41	10.19	17.6	11.75	0.32	0.10	0.11	0.07	66.41
19-24	IIB24	5.47	9.39	16.2	10.48	0.14	0.07	0.07	0.05	70.89
24-31	IIB25	5.05	7.16	12.3	12.93	0.09	0.07	0.10	0.04	62.32
31-42	IIB26	4.95	7.09	12.2	10.33	0.07	0.04	0.08	0.07	68.48
42-51	IIB27	4.84	6.23	10.7	9.51	0.08	0.04	0.08	0.04	70.24
51-59	IIB28	4.75	6.52	11.2	11.54	0.11	0.08	0.08	0.03	62.22

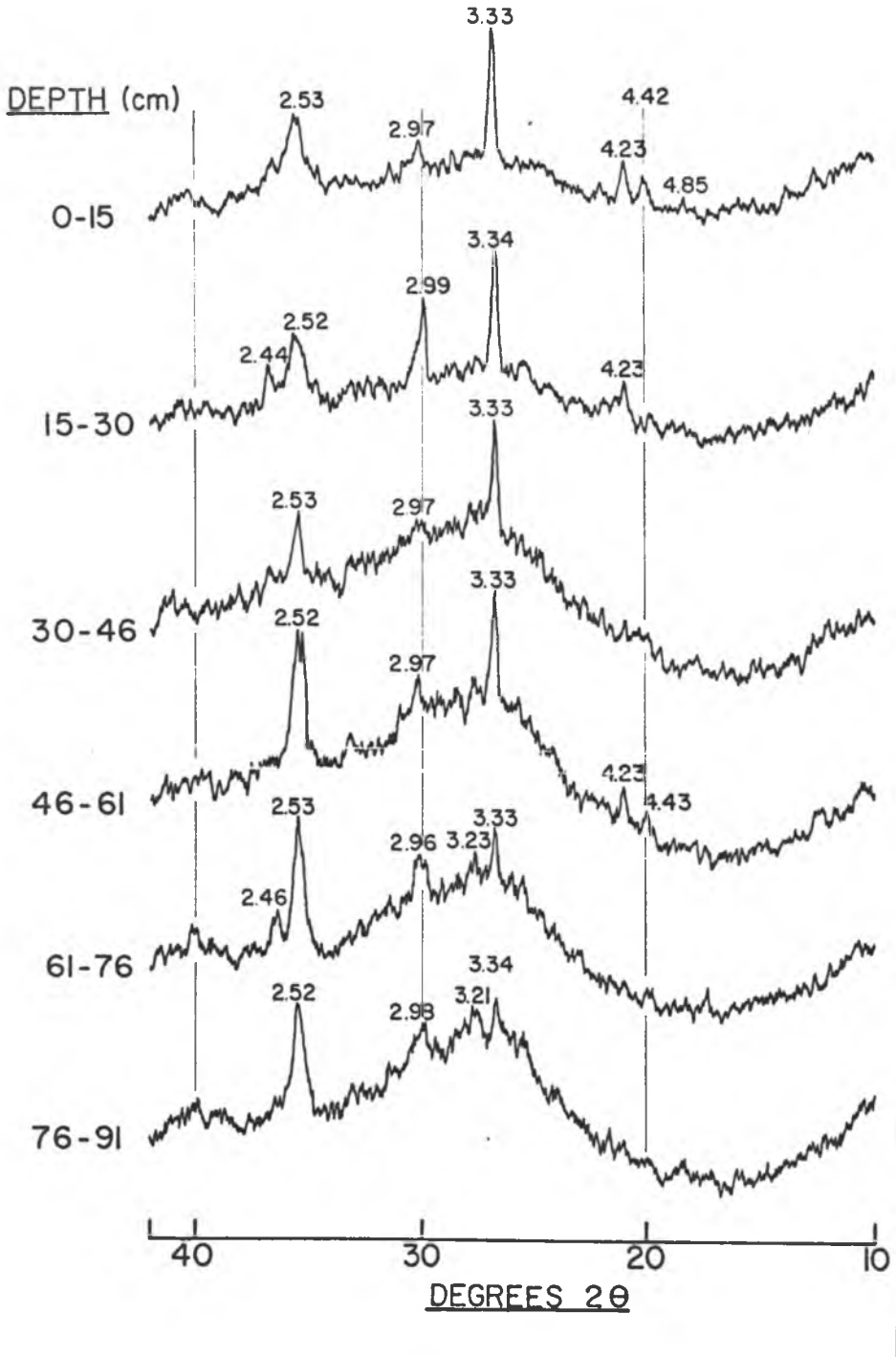

Fig. 6. X-ray diffraction patterns of the Maile silty clay loam profile

Table 5. The effect of $CaSiO_3$ on soil pH with depth[1]

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)									
	0		6.72		13.44		26.88		53.76	
0-15	4.88	h[2]	5.12	gh	5.50	efg	5.72	bcdef	6.33	a
15-30	5.12	gh	5.35	fg	5.48	efg	5.78	bcde	6.32	a
30-46	5.57	cdef	5.53	def	5.48	efg	5.68	bcdef	5.91	bcd
46-61	5.57	cdef	5.75	bcde	5.59	bcdef	5.69	bcdef	5.80	bcde
61-76	5.48	efg	5.73	bcdef	5.69	bcdef	5.69	bcdef	5.93	bc
76-91	5.46	efg	5.81	bcde	5.76	bcde	5.73	bcdef	5.97	ab

[1]Averages of 3 replicates.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

Table 6. The effect of $CaSiO_3$ on exchangeable K (ppm) with depth[1]

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)									
	0		6.72		13.44		26.88		53.76	
0-15	91.7	efghi[2]	131.3	cdefghi	258.0	ab	276.7	a	232.7	abc
15-30	149.4	bcdefgh	163.2	abcdefg	215.0	abcd	200.0	abcde	175.3	abcdef
30-46	130.9	cdefghi	132.3	cdefghi	87.3	efghi	68.6	fghi	74.8	fghi
46-61	81.4	fghi	92.9	efghi	57.7	fghi	36.2	hi	57.3	ghi
61-76	97.8	defghi	87.5	efghi	51.5	ghi	40.0	hi	46.2	ghi
76-91	79.7	fghi	69.5	fghi	45.3	hi	26.1	i	43.7	hi

[1]Averages of 3 replicates.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

Table 7. Percent of Total Exchangeable K in each Treatment Profile

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)				
	0	6.72	13.44	26.88	53.76
0-15	14.5	19.4	36.1	42.7	36.9
15-30	23.7	24.1	30.1	30.9	27.8
30-46	20.8	19.6	12.2	10.6	11.9
46-61	12.9	13.7	8.1	5.6	9.1
61-76	15.5	12.9	7.2	6.2	7.3
76-91	12.6	10.3	6.3	4.0	6.9

Table 8. The effect of $CaSiO_3$ on exchangeable Ca (ppm) with depth[1]

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)									
	0		6.72		13.44		26.88		53.76	
0-15	378	ijkl[2]	768	ghijk	2016	d	3408	c	5024	a
15-30	490	hijkl	1165	efg	1845	d	2915	c	4357	b
30-46	259	jkl	931	efghi	869	efghij	1093	efgh	1472	def
46-61	187	kl	592	ghijkl	707	ghijkl	856	fghij	1499	de
61-76	170	kl	565	ghijkl	641	ghijkl	701	ghijkl	978	efghi
76-91	96	l	490	hijkl	510	hijkl	409	ijkl	691	ghijkl

[1]Averages of 3 replicates.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

Table 9. Percent of Total Exchangeable Ca in each Treatment Profile

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)				
	0	6.72	13.44	26.88	53.76
0-15	23.9	17.0	30.6	36.3	35.1
15-30	31.0	25.8	28.0	31.1	30.4
30-46	16.4	20.6	13.2	11.7	10.3
46-61	11.8	13.1	10.7	9.1	10.5
61-76	10.8	12.5	9.7	7.5	6.8
76-91	6.1	10.9	7.7	4.4	4.8

Table 10. The effect of $CaSiO_3$ on exchangeable Mg (ppm) with depth[1]

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)									
	0		6.72		13.44		26.88		53.76	
0-15	14.5	h[2]	35.7	fgh	90.0	bcd	125.2	ab	148.7	a
15-30	27.9	fgh	80.7	cde	100.7	bc	120.7	ab	123.0	ab
30-46	26.0	fgh	78.8	cde	37.8	fgh	48.3	efgh	41.0	fgh
46-61	13.8	h	61.7	def	41.3	fgh	38.0	fgh	31.7	fgh
61-76	16.7	gh	51.5	efg	50.7	efgh	27.8	fgh	27.8	fgh
76-91	21.5	gh	51.7	efg	41.7	fgh	17.7	gh	20.5	gh

[1]Averages of 3 replicates.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

Table 11. Percent of Total Exchangeable Mg in each Treatment Profile

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)				
	0	6.72	13.44	26.88	53.76
0-15	12.0	9.9	24.9	33.2	37.9
15-30	23.2	22.4	27.8	32.0	31.3
30-46	21.6	21.9	10.4	12.8	10.4
46-61	11.5	17.1	11.4	10.1	8.1
61-76	13.9	14.3	14.0	7.4	7.1
76-91	17.9	14.4	11.5	4.7	5.2

Table 12. The effect of $CaSiO_3$ on water extractable silicon (ppm) with depth[1]

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)									
	0		6.72		13.44		26.88		53.76	
0-15	15.8	def[2]	17.2	de	19.2	cd	26.9	b	34.4	a
15-30	13.5	defgh	14.7	defg	17.1	de	24.4	bc	26.3	b
30-46	9.1	fghijk	10.4	efghijk	13.5	defgh	16.8	de	12.6	defghi
46-61	6.1	ijk	7.7	hijk	11.6	efghij	9.8	fghijk	8.1	ghijk
61-76	5.7	jk	5.6	jk	8.4	ghijk	7.8	hijk	7.6	hijk
76-91	5.7	jk	4.7	k	6.9	hijk	6.9	hijk	7.3	hijk

[1]Averages of 3 replicates.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

Table 13. Percent of Total Water-Extractable Silicon in each Treatment Profile

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)				
	0	6.72	13.44	26.88	53.76
0-15	28.3	28.5	25.0	29.1	35.7
15-30	24.2	24.4	22.3	26.4	27.3
30-46	16.3	17.3	17.6	18.1	13.1
46-61	10.9	12.8	15.1	10.6	8.4
61-76	10.2	9.3	11.0	8.4	7.9
76-91	10.2	7.8	9.0	7.5	7.6

Table 14. The effect of $CaSiO_3$ on the average pH, CEC, exchangeable Ca and Mg, and water extractable Si of a profile

$CaSiO_3$ Rate (M.T./ha)	pH	CEC[1] (meq/100g)	Ca (ppm)	Mg (ppm)	Si (ppm)
0	5.35 D[2]	48.63 C	263 E	20.1 B	9.3 C
6.72	5.55 C	50.57 BC	752 D	60.0 A	10.0 C
13.44	5.58 C	53.68 BC	1098 C	60.4 A	12.8 B
26.88	5.72 B	55.51 B	1564 B	62.9 A	15.4 A
53.76	6.04 A	63.53 A	2337 A	65.5 A	16.0 A

[1]CEC taken from average of 3 replicates at surface 0-15 cm. All other analyses are averages of 18 observations.

[2]Averages followed by the same letter are not significantly different from each other at the 5% level.

Table 15. The effect of $CaSiO_3$ on the distribution of exchangeable Ca, Mg, K, and H_2O extractable Si in a Profile

IDENTIFICATION		MEANS (Average of 15 Observations)				
No.	DEPTH (cm)	Ca (ppm)	Mg (ppm)	K (ppm)	Si (ppm)	% H_2O
1	0-15	2319 A*	90.6 A	198.1 A	22.7 A	74.98 E
2	15-30	2155 A	82.8 A	180.6 A	19.2 B	136.14 D
3	30-46	925 B	46.4 B	98.8 B	12.5 C	195.14 C
4	46-61	768 BC	37.3 BC	65.1 BC	8.7 D	209.91 B
5	61-76	611 CD	34.8 BC	64.6 BC	7.0 DE	221.76 AB
6	76-91	439 D	30.6 C	52.9 C	6.3 E	229.70 A

*P<.05
Means followed by the same letter are not significantly different from each other.

Table 16. Percent Moisture in Soil

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)				
	0	6.72	13.44	26.88	53.76
0-15	72.87	77.37	76.49	73.97	74.18
15-30	130.45	124.72	120.98	150.68	153.86
30-46	207.95	196.40	170.38	211.50	189.46
46-61	203.13	200.52	217.29	224.04	204.57
61-76	228.47	226.70	217.29	225.00	211.35
76-91	248.34	237.13	215.16	224.79	223.08

Table 17. Extractable Soil P by the Modified Truog Method (ppm)

Depth (cm)	$CaSiO_3$ Applied (metric tons/hectare)				
	0	6.72	13.44	26.88	53.76
0-15	24.2	30.2	27.2	24.6	21.5
15-30	13.5	18.2	21.2	11.4	8.1
30-46	3.7	5.2	7.5	4.1	5.2
46-61	4.6	4.3	4.6	3.8	4.0
61-76	4.0	4.3	3.5	3.8	3.5
76-91	3.6	3.9	3.9	2.9	3.2

LIST OF REFERENCES

1. Ayres, A. S. 1961. Liming Hawaiian Sugar Cane Soils. Hawaiian Planters' Record. 56:227-244.

2. Ayres, A. S. and H. H. Hagihara. 1953. Effect of the Anion on the Sorption of Potassium by Some Humic and Hydrol Humic Latosols. Soil Sci. 75(1):1-17.

3. Bartlett, R. J. and J. L. McIntosh. 1969. pH-Dependent Bonding of Potassium by a Spodosol. Soil Sci. Soc. Am. Proc. 33:535-539.

4. Beckett, P. H. T. 1964. Potassium-Calcium Exchange Equilibria in Soils: Specific Adsorption Sites for Potassium. Soil Sci. 97: 376-383.

5. Bhumbla, D. R. and E. O. McLean. 1965. Aluminum in Soil. VI. Changes in pH-Dependent Acidity, Cation-Exchange Capacity, and Extractable Aluminum with Addition of Lime to Acid Surface Soils. Soil Sci. Soc. Am. Proc. 29:370-374.

6. Birrell, K. S. 1958. Reactions of Amorphous Soil Colloids with Ions in Solution. New Zealand Soc. Soil Sci. Proc. 3:11-13.

7. Birrell, K. S. and M. Gradwell. 1956. Ion-Exchange Phenomena in Some Soils Containing Amorphous Mineral Constituents. J. Soil Sci. 7:130-147.

8. Bolt, G. H., M. E. Sumner, and A. Kamphorst. 1963. A Study of the Equilibria Between Three Categories of Potassium in an Illitic Soil. Soil Sci. Soc. Am. Proc. 27:294-299.

9. Burgess, P. S. 1923. Comparison of Active Aluminum and Hydrogen Ion Concentrations of Widely Separated Acid Soils. Soil Sci. 15(5): 407-412.

10. Coleman, N. T., S. B. Weed, and R. J. McCracken. 1959. Cation-Exchange Capacity and Exchangeable Cations in Piedmont Soils of North Carolina. Soil Sci. Soc. Am. Proc. 23:146-149.

11. Davis, F. L. 1945. Retention of Phosphates by Soils: II. Effect of Drying and of Certain Cations and Anions on the Cation Exchange Capacity of Soils. Soil Sci. 59:175-190.

12. de Villiers, J. M. and M. L. Jackson. 1967. Cation-Exchange Capacity Variations with pH in Soil Clays. Soil Sci. Soc. Am. Proc. 31:473-476.

13. Duncan, D. B. 1965. A Bayesian Approach to Multiple Comparisons. Technometrics 7:171-222.

14. Greenland, D. J. 1971. Interactions Between Humic and Fulvic Acids and Clays. Soil Sci. 111:34-41.

15. Hanna, W. G. and J. F. Reed. 1948. A Comparison of Ammonium Acetate and Buffered Barium Chloride Methods of Determining Cation-Exchange Properties of Limed Soils. Soil Sci. 66:447.

16. Helling, C. S., G. Chesters, and R. B. Corey. 1964. Contributions of Organic Matter and Clay to Soil Cation Exchange Capacity as Affected by the pH of the Saturating Solution. Soil Sci. Soc. Am. Proc. 28:517-520.

17. Hough, G. J., P. L. Gile, and Z. C. Foster. 1941. Rock Weathering and Soil Profile Development in the Hawaiian Islands. U.S.D.A. Tech. Bull. 752.

18. Houng, K. H., G. Uehara, and G. D. Sherman. 1966. On the Exchange Properties of Allophanic Clays. Pacific Science. Vol. XX. No. 4. 507-514.

19. Ikawa, H. 1972. Unpublished data: Soil Survey of the Branch Station, Hawaii Agric. Exp. Station.

20. Jarusov, S. S. 1937. Mobility of Exchangeable Cations in the Soil. Soil Sci. 43:285-303.

21. Kanehiro, Y., and G. D. Sherman. 1956. Effect of Dehydration-Rehydration on Cation Exchange Capacity of Hawaiian Soils. Soil Sci. Soc. Am. Proc. 20(3):341-344.

22. Kilmer, V. J. 1965. Silicon. In C. A. Black (ed.) Methods of Soil Analysis. Part 2. American Society of Agronomy, Madison, Wisconsin.

23. Loganathan, P. 1967. The Properties and Genesis of Four Middle Altitude Dystrandepts from Mauna Kea, Hawaii. Master's Thesis. Univ. of Hawaii, Honolulu.

24. Magistad, O. C. 1925. The Aluminum Content of the Soil Solution and its Relation to Soil Reaction and Plant Growth. Soil Sci. 20: 181-225.

25. Mahilum, B. C., R. L. Fox, and J. A. Silva. 1970. Residual Effects of Liming Volcanic Ash Soils in the Humid Tropics. Soil Sci. 100(2): 102-109.

26. McLean, E. O., and E. J. Owen. 1969. Effects of pH on the Contributions of Organic Matter and Clay to Soil Cation Exchange Capacities. Soil Sci. Soc. Am. Proc. 33:855-858.

27. McLean, E. O., D. C. Reicosky, and C. Lakshmanan. 1965. Aluminum in Soils: VII. Interrelationships of Organic Matter, Liming and Extractable Aluminum with "Permanent Charge" (KCl) and pH-dependent Cation Exchange Capacity of Surface Soils. Soil Sci. Soc. Am. Proc. 29:374-378.

28. Mekaru, T. and G. Uehara. 1972. Anion Adsorption in Ferruginous Tropical Soils. Soil Sci. Soc. Am. Proc. 36:296-300.

29. Monteith, N. H. and G. D. Sherman. 1963. The Comparative Effects of Calcium Carbonate and of Calcium Silicate on the Yield of Sudan Grass Grown in a Ferruginous Latosol and a Hydrol Humic Latosol. Hawaii Agric. Exp. Sta. Tech. Bull. No. 53. 44 p.

30. Munson, R. D. and W. L. Nelson. 1963. Movement of Applied Potassium in Soils. Jour. Agr. and Food Chem. 11. No. 3. 193-201.

31. Onikura, Y. 1959. Effects of Artificial Silication on Volcanic Ash Soils. III. Incremental Silication on Volcanic Ash Soils. J. Sci. Soil Tokyo, 30. 455-458.

32. Paver, H. and C. E. Marshall. 1934. The Role of Aluminum in the Reactions of Clays. Jour. Soc. Chem. Ind. (London) 53:750-760.

33. Pratt, P. F. 1961. Effect of pH on the Cation-Exchange Capacity of Surface Soils. Soil Sci. Soc. Am. Proc. 24:96-98.

34. Pratt, P. F. and N. Hollowaychuk. 1954. A Comparison of Ammonium Acetate, Barium Acetate, and Buffered Barium Chloride Methods of Determining Cation Exchange Capacity. Soil Sci. Soc. Am. Proc. 18:365-368.

35. Schofield, R. K. 1949. Effect of pH on Electric Charges Carried by Clay Particles. Jour. Soil Sci. 1:1-8.

36. Seatz, L. F. and E. Winters. 1943. Potassium Release from Soils as Affected by Exchange Capacity and Complimentary Ion. Soil Sci. Soc. Am. Proc. 8:150-153.

37. Sherman, G. D., I. P. S. Dias, and N. H. Monteith. 1964. Calcium Silicate, A New Liming Material. Hawaii Fram Sci., Vol. 13, No. 3. 8-9.

38. Snedecor, G. W. and W. G. Cochran. 1967. Statistical Methods. 6th ed. Iowa State College Press, Ames, Iowa.

39. Suehisa, R. H., O. R. Younge, and G. D. Sherman. 1963. Effects of Silicates on Phosphorus Availability to Sudan Grass Grown on Hawaiian Soils. Hawaii Agric. Exp. Sta. Tech. Bull. No. 51. 40 p.

40. Swindale, L. D. 1964. The Properties of Soils Derived from Volcanic Ash. Report on the "Meeting on the Classification and Correlation of Soils from Volcanic Ash." World Soil Resources Report 14. FAO, Rome, 1965.

41. Syed-Fadzil, Syed-Farooq bin. 1972. Ion Retention and Movement in Soils with Variable Charge Colloids. Master's Thesis. Univ. of Hawaii, Honolulu.

42. Tamimi, YV N., D. T. Matsuyama, and S. A. El-Swaify. 1972. Effect of $CaCO_3$, $CaSiO_3$, and P on pH Dependent Charges and Cation Retention in a Hydric Dystrandept in Hawaii. Agronomy Abstracts. 64th Annual Meeting. Amer. Soc. of Agron. p. 89.

43. Uehara, G., H. Ikawa, and H. H. Asato. 1971. Guide to Hawaii Soils. College of Tropical Agriculture, Hawaii Agricultural Experiment Station. Miscellaneous Publications 83.

44. Van Raij, B. and M. Peech. 1972. Electrochemical Properties of Some Oxisols and Alfisols of the Tropics. Soil Sci. Soc. Am. Proc. 36:587-593.

45. Voelcher, A. 1873. Annual Report of the Consulting Chemist, Roy. Agric. Soc. Eng. for 1873. Jour. Roy. Agric. Soc. Eng. X:277-287.

46. Wada, K. and H. Ataka. 1958. The Ion-uptake Mechanism of Allophane. Soil Plant Food (Tokyo) 4(1):12-18.